



Process Development and Microstructural Characterization on Friction Plug Welded 2195 and 2219 Alloys

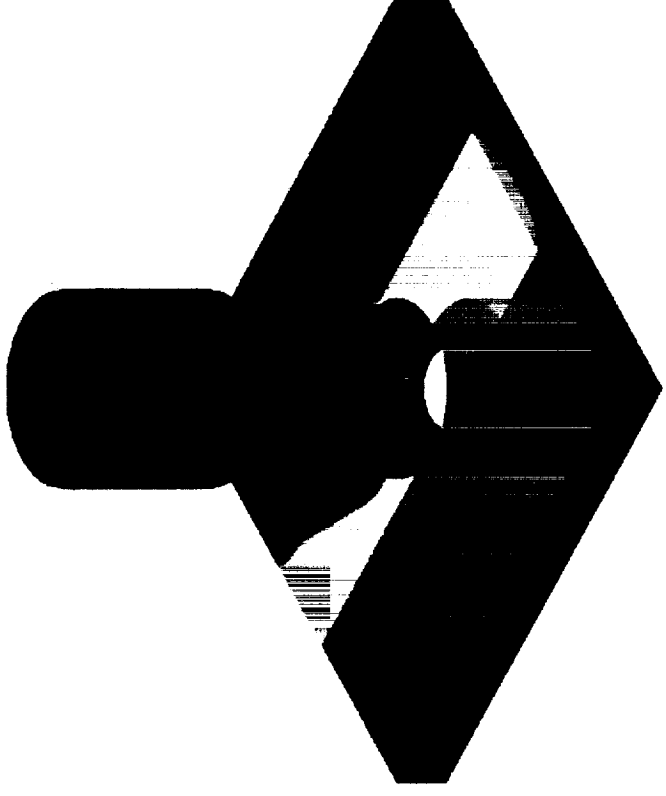
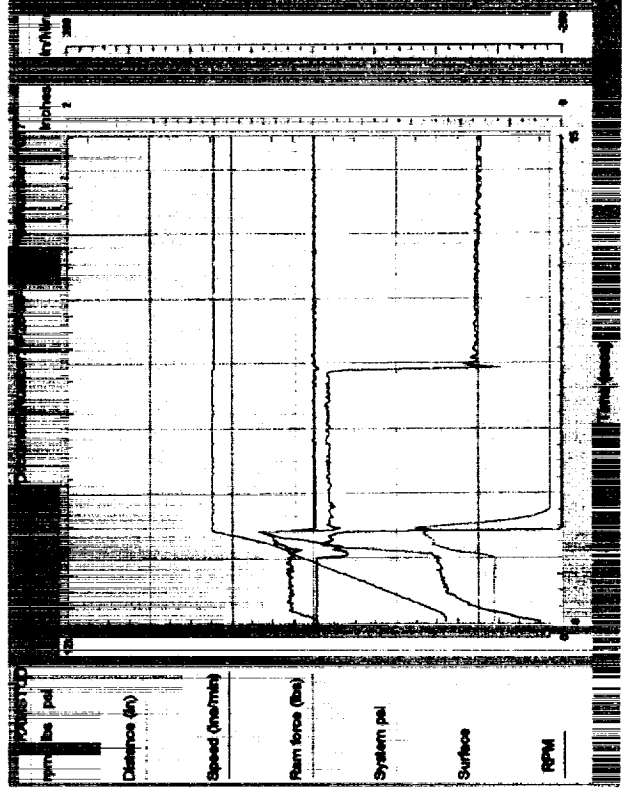
Z.X. Li, M.A. Cantrell, and R.J. Brown
Program and Technology Development
Lockheed Martin Michoud Space Systems
New Orleans, LA 70189

Outline

- Push FPW Repair of Fusion Weld Defect and FSW Key Hole
- Push FPW Process Development on Thin (0.140") and Thick (0.500" & 0.650") Gages
- Microstructural analysis
- Mechanical Property of Stitch FPW and Photo Stress Analysis
- Conclusions

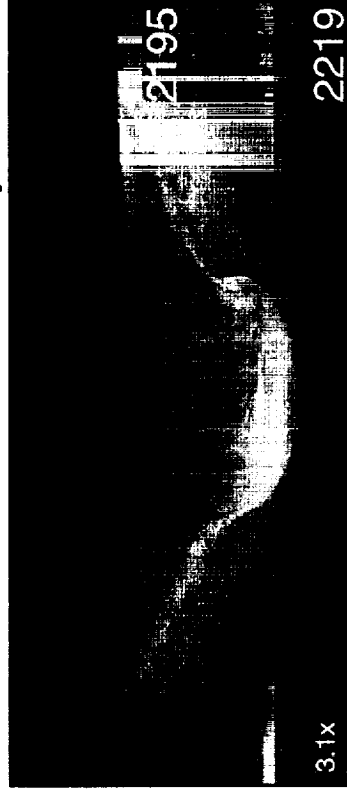
Friction Plug Welding Process

- **FPW process**
 - Drilling a tapered hole to remove weld defect;
 - Heating phase: tapered plug spins into hole at high rotation speed & pressure to generate friction heat in order to plastize the interface;
 - Forging phase: subsequent forging pressure is applied to have an intimate contact at the interface to allow metallurgical bonding (recrystallization).



Push FPW Repair of FSW Key Hole

Simultaneous Butt and Lap FSW



Friction Stir Weld Keyhole



Friction Stir Welding Parameters:

- **Rotation Speed** - 252 RPM CCW
- **Travel Speed** - 3.75 IPM
- **Plunge Depth** - 0.010" Heel Plunge
- **Material** - 2195/2195 butt, 2195/2219 lap
- **Pin Tool** - 0.320 Standard
 - 0.315" Pin Height
 - 0.426" Pin Depth
 - 1.11" Shoulder Diameter

Push FPW Repair of FSW Key Hole

Friction Push Weld Parameters:

- **Plug** - 2195 T8
 - 60° primary angle
 - 130° secondary angle
 - 0.750" major diameter
- **Plate Hole** -
 - 60° primary angle
 - 130° secondary angle
 - 0.750" major diameter
 - 0.340" minor diameter
- **Weld Schedule** -
 - Spindle Speed - 5500 RPM
 - Ram Speed - 16 IPM
 - Heating Load - 8000 lbs
 - Forging Load - 8000 lbs
 - Heating Displacement - 0.125"

Friction Plug Tapered Hole



Plug Hole Configuration



**Used 2219 Frame as a consumable
anvil for forging plug flash**

Push FPW Repair of FSW Key Hole

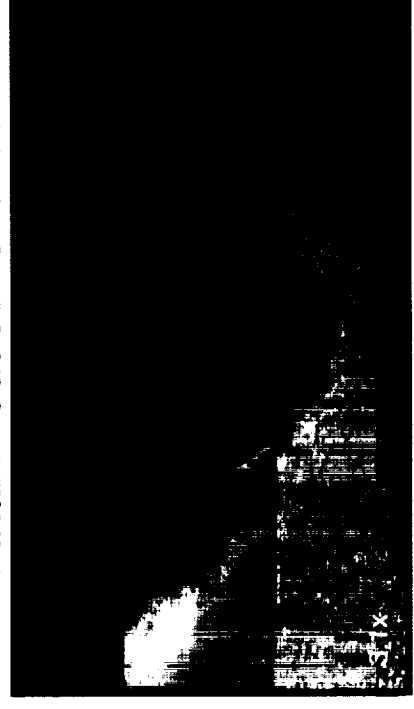
Push Plug Repair Results:

- Non-Destructive Evaluation
 - No X-Ray Indications
 - No Penetrant Indications
- Mechanical Strength
 - 2 Pass FSW = 43.7 ksi
 - 2 Pass FSW/FPW = 43.5 ksi

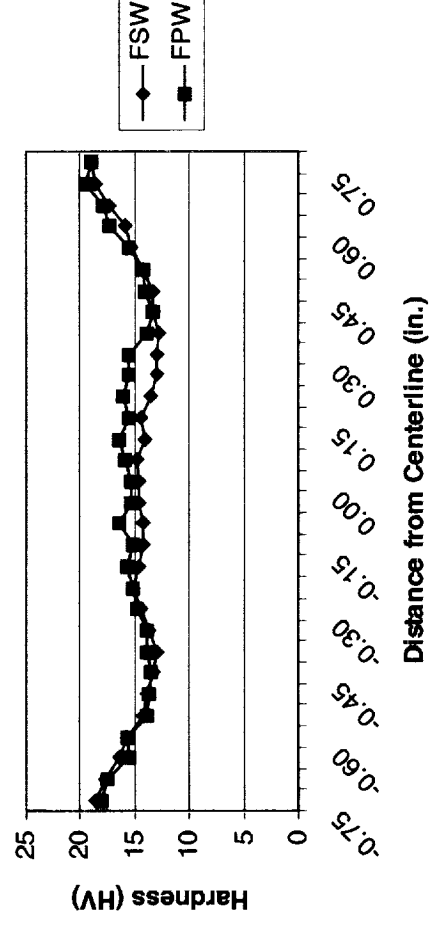
Keyhole Closeout - As Welded



Final Product - Shaved

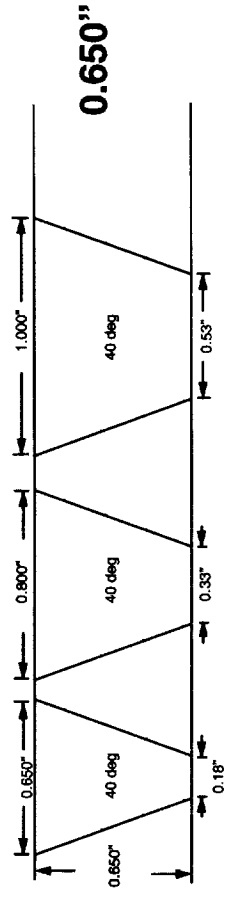
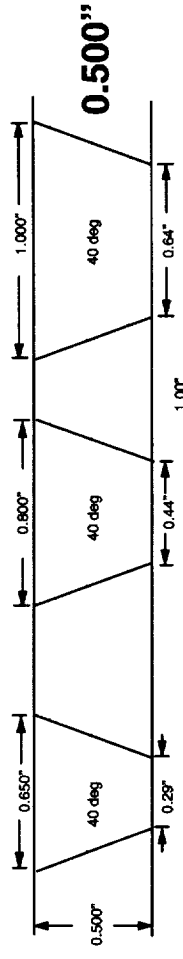
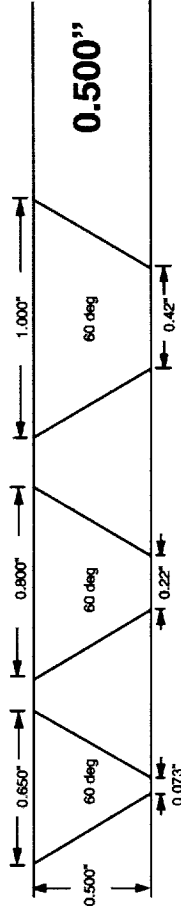
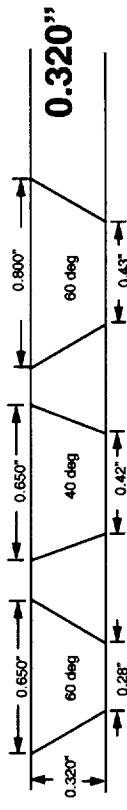
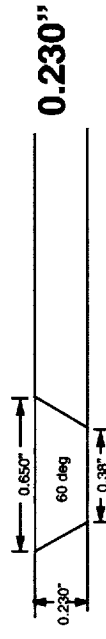
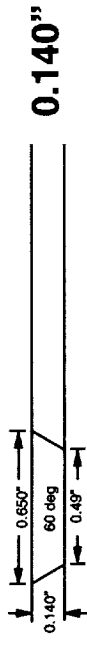


Microhardness of FSW vs. FPW



FPW Process Development on Thin & Thick Gages

- To select plug size and angle
 - plug hole minor diameter needs to be large enough to
 - remove defects at back side;
 - push shear bands down to backing button area.



FPW Process Development

- Effect of Heating/Forging Pressures



10,000 lbs



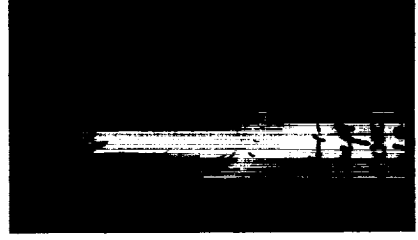
6,000 lbs

Not enough pressure to form plate flash

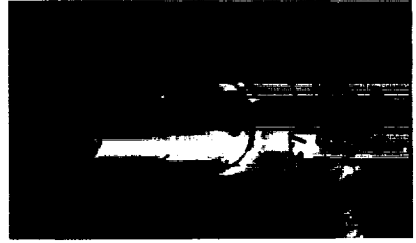
0.800"/40 deg. Plugs on
0.650" thick 2195 VPPA welds

Backing button depth: 0.200"
Heating Displacement: 0.150"

- Effect of Heating Displacement



Heating Displ. 0.100"



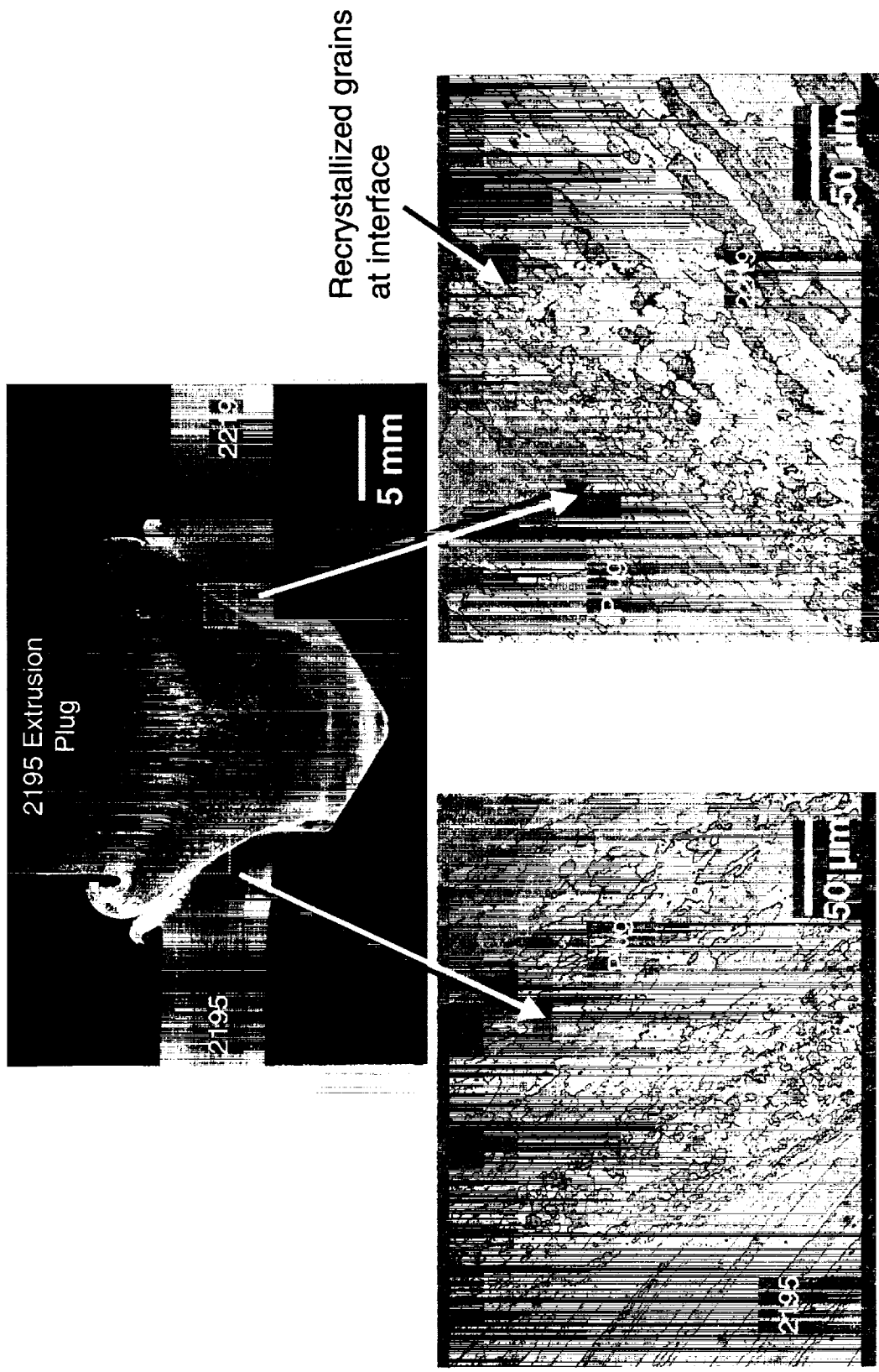
Heating Displ. 0.050"

Backing button depth: 0.275"
Heating/Forging Pressure: 10,000 lbs

Not enough heating displacement
to form plug/plate flash

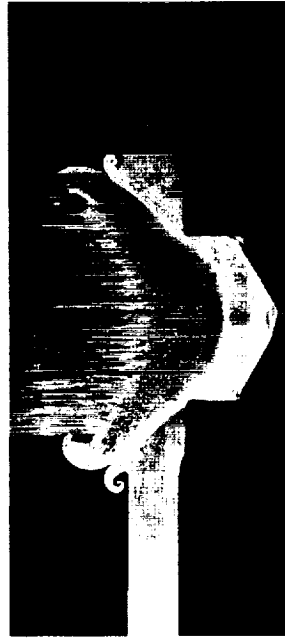
Microstructural Analysis

Friction plug welding on 0.230" thick 2195 to 2219 fusion weld



FPW Process Development

- FPW on 0.140" Gage



0.650"/60° plug weld

- To prevent push-through at thin gage
 - Smaller hole size <0.650")
 - medium heating displacement

Effect of Hole Size, Load, and Heating Displacement.

| Sample # | Trial | Hole Size in. | Load lbs | Heating Disp. in. |
|------------------|-------|------------------|-------------|----------------------|
| 766-2 | 7 | 500 | 8000 | 100 |
| 766-3 | 6 | 550 | 10000 | 100 |
| 766-4 | 13 | 550 | 6000 | 50 |
| 766-5 | 10 | 600 | 6000 | 100 |
| 766-6 | 2 | 600 | 8000 | 50 |
| 766-7 | 15 | 500 | 8000 | 50 |
| 767-8 | 9 | 500 | 6000 | 50 |
| 767-9 | 4 | 500 | 6000 | 150 |
| 767-10 | 11 | 600 | 10000 | 100 |
| 766-1 | 5 | 600 | 10000 | 150 |
| 767-11 | 12 | 550 | 10000 | 50 |
| 767-12 | 1 | 500 | 10000 | 150 |
| 767-13A, 803-13B | 14 | 600 | 8000 | 150 |
| 803-14A, 803-14B | 8 | 550 | 8000 | 150 |
| 803-15 | 3 | 500 | 10000 | 50 |

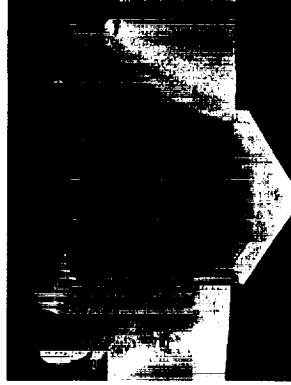
| Sample Number | Pre-Proof NDE | | | Pre-Proof NDE | | | Proof | | | Post-Proof NDE | | | UTS (ksi) | |
|---------------|---------------|-----|-----|---------------|-----|-----|-------|-------|------|----------------|-----|-----|-----------|-------|
| | RT | PT | UT | RT | PT | UT | Load | Score | Load | RT | PT | UT | Score | At RT |
| 766-1 | Acc | Acc | Acc | Acc | Acc | Acc | 31.1 | 0 | 31.1 | Acc | Acc | Acc | 0 | 49.2 |
| 766-2 | Acc | Acc | Acc | Acc | Acc | Acc | 29.9 | 0 | 29.9 | Acc | Acc | Acc | 0 | 47.9 |
| 766-3 | Acc | Acc | Acc | Acc | Acc | Acc | 30.8 | 0 | 30.8 | Acc | Acc | Acc | 0 | 46.5 |
| 766-4 | Rej | Rej | Acc | Acc | Rej | Acc | 30.0 | 2 | 30.0 | Acc | Rej | Rej | 2 | 39.9 |
| 766-5 | Acc | Acc | Acc | Acc | Acc | Acc | 29.6 | 0 | 29.6 | Acc | Acc | Acc | 0 | 46.5 |
| 766-6 | Acc | Acc | Acc | Acc | Acc | Acc | 29.8 | 0 | 29.8 | Acc | Acc | Acc | 0 | 48.9 |
| 766-7 | Acc | Rej | Acc | Acc | Rej | Acc | 30.4 | 1 | 30.4 | Acc | Rej | Rej | 2 | 42.7 |
| 767-8 | ACC | Rej | Acc | Acc | Rej | Acc | 30.2 | 1 | 30.2 | Acc | Rej | Rej | 2 | 43.7 |
| 767-9 | Acc | Acc | Acc | Acc | Acc | Acc | 31.1 | 0 | 31.1 | Acc | Acc | Acc | 0 | 49.2 |
| 767-10 | Acc | Acc | Acc | Acc | Acc | Acc | 31.1 | 0 | 31.1 | Acc | Acc | Acc | 0 | 49.1 |
| 767-11 | Acc | Rej | Acc | Acc | Rej | Acc | 31.3 | 1 | 31.3 | Acc | Acc | Acc | 0 | 51.3 |
| 767-12 | Acc | Acc | Acc | Acc | Acc | Acc | 29.9 | 0 | 29.9 | Acc | Acc | Acc | 0 | 45.5 |
| 767-13A | Acc | Acc | Acc | Acc | Acc | Acc | 30.1 | 0 | 30.1 | Acc | Acc | Acc | 0 | 46.5 |
| 803-13B | Acc | Acc | Acc | Acc | Acc | Acc | 30.8 | 0 | 30.8 | Acc | Acc | Acc | 0 | 46.6 |
| 803-14A | Acc | Acc | Acc | Acc | Acc | Acc | 31.8 | 0 | 31.8 | Acc | Acc | Acc | 0 | 49.1 |
| 803-14B | Acc | Acc | Acc | Acc | Acc | Acc | 31.0 | 0 | 31.0 | Acc | Acc | Acc | 0 | 49.4 |
| 803-15 | Acc | Rej | Acc | Acc | Rej | Acc | 30.8 | 1 | 30.8 | Acc | Rej | Acc | 1 | 47.7 |

FPW Process Development

- FPW on 0.500" Gage



0.800"/40° plug weld



1.000"/40° plug weld

Minor diameter needs to be large enough to push shear band into backing button area

Effect of Backing Button Depth, Load, and Heating Displacement

| Sample # | Backing Button Depth (in) | Load (lbs) | Burn-off (in) |
|-------------|---------------------------|------------|---------------|
| TL-5145-1 | 0.200 | 8000 | 0.100 |
| TL-5145-2 | 0.200 | 8000 | 0.050 |
| TL-5145-3 | 0.200 | 6000 | 0.050 |
| TL-5145-4 | 0.200 | 6000 | 0.150 |
| TL-5145-5 | 0.200 | 10000 | 0.150 |
| TL-5145-6 | 0.200 | 10000 | 0.050 |
| TL-5145-7 | 0.275 | 10000 | 0.100 |
| TP-764-1-8 | 0.350 | 10000 | 0.150 |
| TP-764-1-9 | 0.275 | 10000 | 0.050 |
| TP-764-1-10 | 0.350 | 8000 | 0.150 |
| TP-764-1-11 | 0.275 | 6000 | 0.050 |
| TP-764-1-12 | 0.350 | 8000 | 0.050 |
| TP-764-1-13 | 0.350 | 6000 | 0.100 |
| TP-763-1-14 | 0.350 | 10000 | 0.100 |
| TP-763-1-15 | 0.275 | 8000 | 0.100 |

| Sample # | Pre-Proof NDE | | | Pre-Proof NDE | | | Pre-Proof | | | Post-Proof NDE | | | Post-Proof NDE | | | FTU (ksi) at RT |
|-------------|---------------|-----|-----|---------------|------------|-----------|-----------|-----|-----|----------------|-----|-----|----------------|----|----|-----------------|
| | RT | PT | UT | Score | Load (ksi) | Pre-Proof | RT | PT | UT | Score | PT | UT | Score | PT | UT | |
| TL-5145-1 | ACC | ACC | ACC | 0 | 30 | | ACC | REJ | ACC | | REJ | ACC | 1 | | | 39.2 |
| TL-5145-2 | ACC | REJ | ACC | 1 | 30 | | ACC | REJ | ACC | | REJ | ACC | 1 | | | 40.8 |
| TL-5145-3 | ACC | REJ | REJ | 2 | 30 | | ACC | REJ | REJ | | REJ | REJ | 2 | | | 41.9 |
| TL-5145-4 | ACC | REJ | ACC | 1 | 30 | | ACC | ACC | ACC | | ACC | ACC | 0 | | | 44.2 |
| TL-5145-5 | ACC | ACC | ACC | 0 | 30 | | ACC | ACC | ACC | | ACC | ACC | 0 | | | 45.2 |
| TL-5145-6 | ACC | ACC | ACC | 0 | 30 | | ACC | ACC | ACC | | ACC | ACC | 0 | | | 42.6 |
| TL-5145-7 | ACC | ACC | ACC | 0 | 30 | | ACC | REJ | REJ | | REJ | REJ | 2 | | | 37.1 |
| TP-764-1-8 | ACC | ACC | ACC | 0 | 30 | | ACC | ACC | ACC | | ACC | ACC | 0 | | | 45.1 |
| TP-764-1-9 | ACC | ACC | ACC | 0 | 30 | | ACC | REJ | REJ | | REJ | REJ | 2 | | | 38.6 |
| TP-764-1-10 | ACC | ACC | ACC | 0 | 30 | | ACC | ACC | ACC | | ACC | ACC | 0 | | | 41.3 |
| TP-764-1-11 | ACC | REJ | REJ | 2 | 30 | | ACC | REJ | REJ | | REJ | REJ | 2 | | | 40.2 |
| TP-764-1-12 | ACC | REJ | REJ | 2 | 30 | | REJ | REJ | REJ | | REJ | REJ | 3 | | | 36.5 |
| TP-764-1-13 | ACC | ACC | ACC | 0 | 30 | | ACC | REJ | ACC | | REJ | ACC | 1 | | | 43.9 |
| TP-763-1-14 | ACC | ACC | ACC | 0 | 30 | | ACC | ACC | ACC | | ACC | ACC | 0 | | | 43.5 |
| TP-763-1-15 | REJ | ACC | REJ | 2 | 30 | | REJ | REJ | REJ | | REJ | REJ | 3 | | | 31.3 |

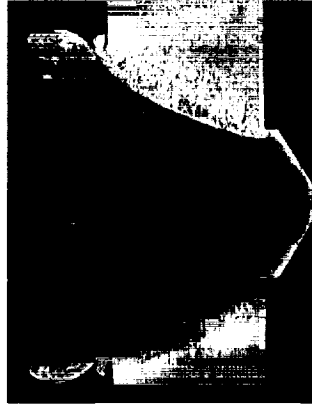
FPW Process Development

Effect of Backing Button Depth, Load, and Heating Displacement

- FPW on 0.650" Gage



0.800"/40° plug weld



1.000"/40° plug weld

Minor diameter needs to be large enough to push shear band into backing button area

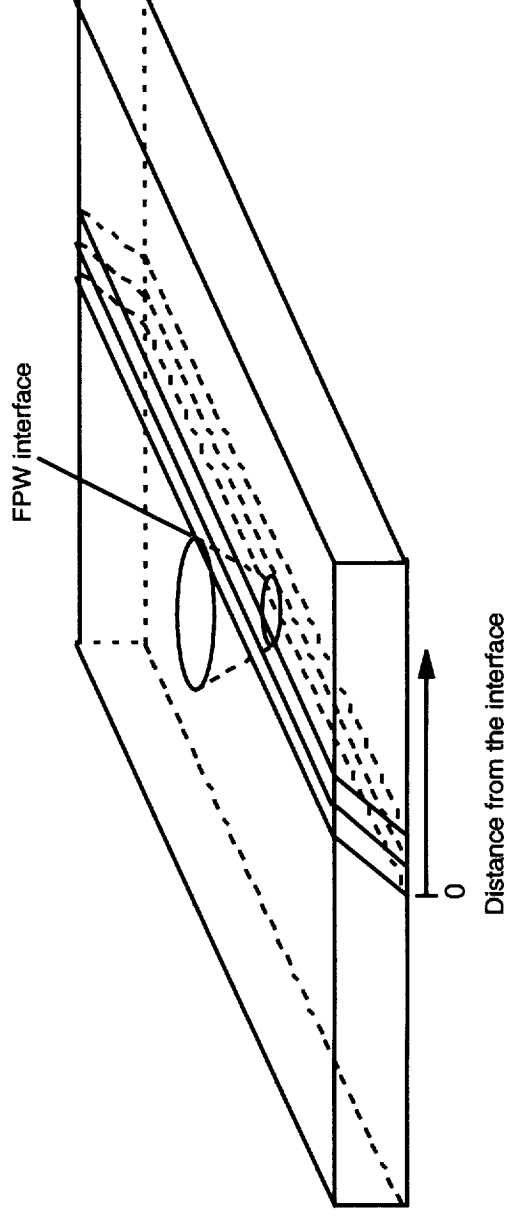
| Sample ID | Backing Button Depth (in) | Load (lbs) | Burn-off (in) |
|-------------|---------------------------|------------|---------------|
| TP-761-1-1 | 0.200 | 10000 | 0.150 |
| -2 | 0.275 | 8000 | 0.150 |
| -3 | 0.200 | 8000 | 0.100 |
| -4 | 0.350 | 6000 | 0.100 |
| -5 | 0.200 | 6000 | 0.050 |
| -6 | 0.275 | 10000 | 0.100 |
| TP-757-1-7 | 0.350 | 8000 | 0.050 |
| -8 | 0.200 | 6000 | 0.150 |
| -9 | 0.275 | 10000 | 0.050 |
| -10 | 0.350 | 8000 | 0.150 |
| -11 | 0.200 | 10000 | 0.050 |
| -12 | 0.350 | 10000 | 0.100 |
| TP-760-1-13 | 0.350 | 10000 | 0.150 |
| -14 | 0.200 | 8000 | 0.050 |
| -15 | 0.275 | 6000 | 0.050 |

| Sample ID | Pre-Proof NDE | | | Pre-Proof Score | Pre-Proof Load (ksi) | Post-Proof NDE | | | Post-Proof Score | FTU (ksi) at RT |
|-------------|---------------|-----|-----|-----------------|----------------------|----------------|-----|-----|------------------|-----------------|
| | RT | PT | UT | | | RT | PT | UT | | |
| TP-761-1-1 | ACC | ACC | ACC | 0 | 30 | ACC | ACC | ACC | 0 | 34.6 |
| -2 | ACC | ACC | ACC | 0 | 30 | ACC | ACC | ACC | 0 | 43.9 |
| -3 | ACC | ACC | ACC | 0 | 30 | ACC | ACC | ACC | 0 | 40.7 |
| -4 | REJ | REJ | REJ | 3 | 30 (failed) | ~ | ~ | ~ | 3 | 30.0 |
| -5 | ACC | REJ | ACC | 1 | 30 | ACC | REJ | ACC | 1 | 41.0 |
| -6 | ACC | ACC | ACC | 0 | 30 | ACC | ACC | REJ | 1 | 41.1 |
| TP-757-1-7 | ACC | ACC | ACC | 0 | 30 | ACC | ACC | ACC | 0 | 39.4 |
| -8 | ACC | REJ | REJ | 2 | 30 | ACC | REJ | REJ | 2 | 36.8 |
| -9 | ACC | REJ | ACC | 1 | 30 | REJ | REJ | REJ | 3 | 36.4 |
| -10 | ACC | REJ | REJ | 2 | 30 | ACC | ACC | ACC | 0 | 40.9 |
| -11 | ACC | ACC | ACC | 0 | 30 | ACC | REJ | ACC | 1 | 38.8 |
| -12 | ACC | ACC | ACC | 0 | 30 | ACC | ACC | ACC | 0 | 44.2 |
| TP-760-1-13 | ACC | REJ | ACC | 1 | 30 | ACC | ACC | ACC | 0 | 36.4 |
| -14 | ACC | ACC | ACC | 0 | 30 | ACC | ACC | ACC | 0 | 36.6 |
| -15 | ACC | REJ | ACC | 1 | 30 | ACC | REJ | ACC | 1 | 37.5 |

Microstructural Analysis

- **TEM Specimen Preparation**

- Cut thin slices 150~200 μm thick from the plug interface toward the HAZ using a diamond wafer saw;
- Punch 3 mm discs in the middle of the slices;
- Twin-jet electro-polish in 25% nitric acid + 75% methanol solution at 15V, -25°C;
- Examine using Philips CM-12 TEM at 120kV.



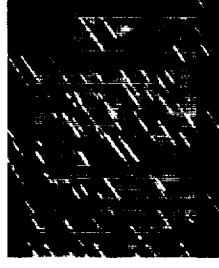
Microstructure and Microhardness Profile of FPW



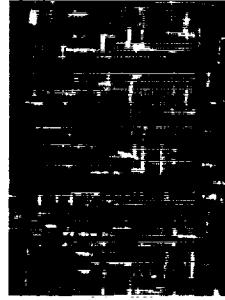
θ' (Al_2Cu) precipitates



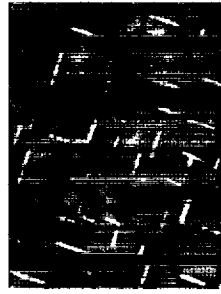
T_1 (Al_2CuLi) precipitates



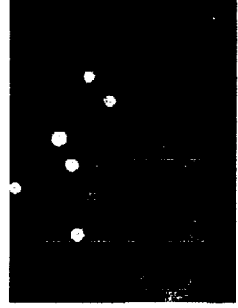
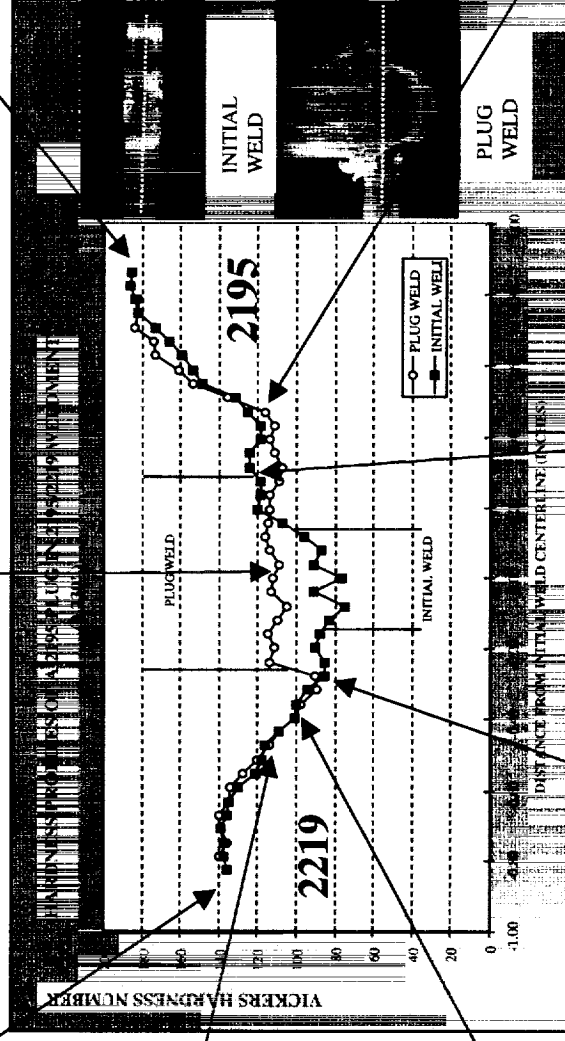
T_1 (Al_2CuLi) precipitates



θ' (Al_2Cu) precipitates



θ' (Al_2Cu) precipitates



Al_3Zr particles



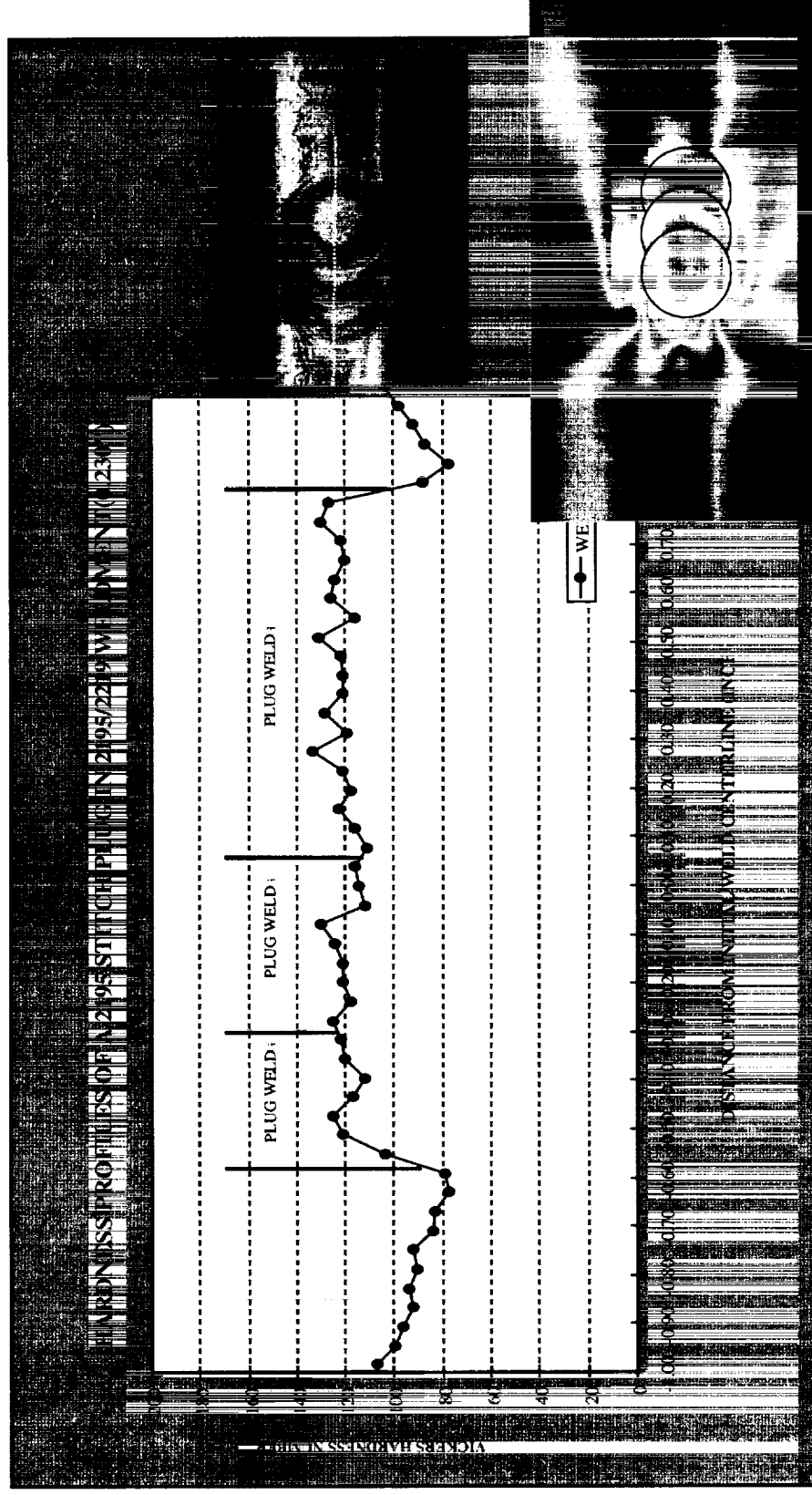
Al_3Zr particles & dislocations



T_1 (Al_2CuLi) precipitates

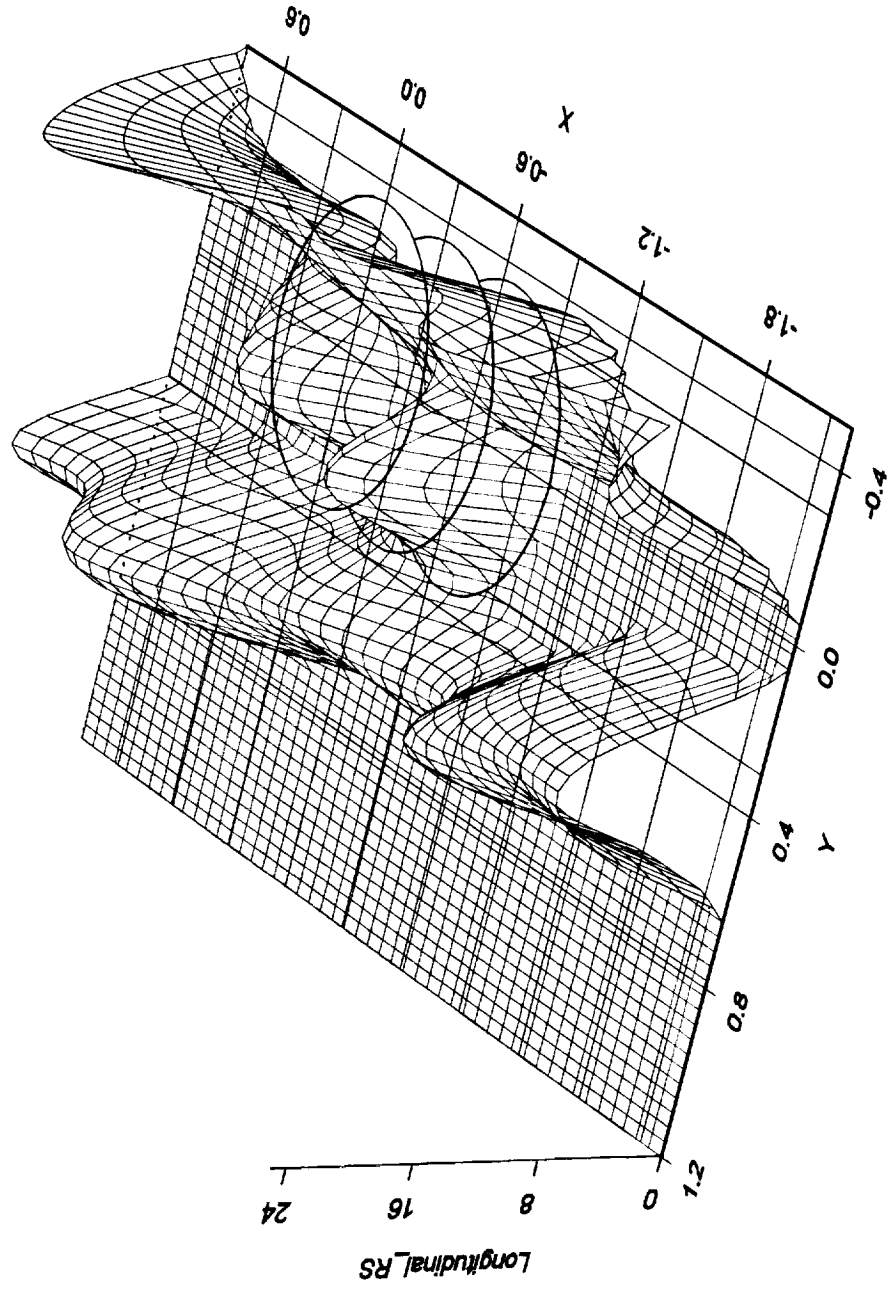
Mechanical Properties of FPW

Microhardness Profile



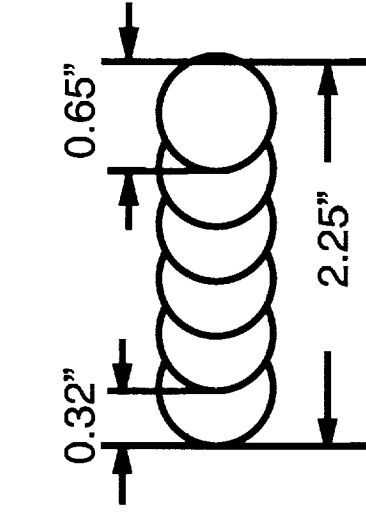
Hardness profile of a triple plug stitch in 2195/2219 weldment

Residual Stress on Triple Stitch FPW

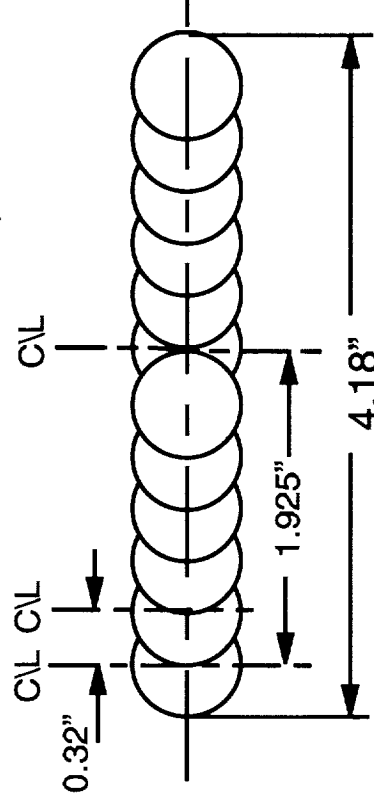


Mechanical Properties of FPW

Photo Stress Testing on Long Stitch Welds



6 plug stitch weld



12 plug stitch weld

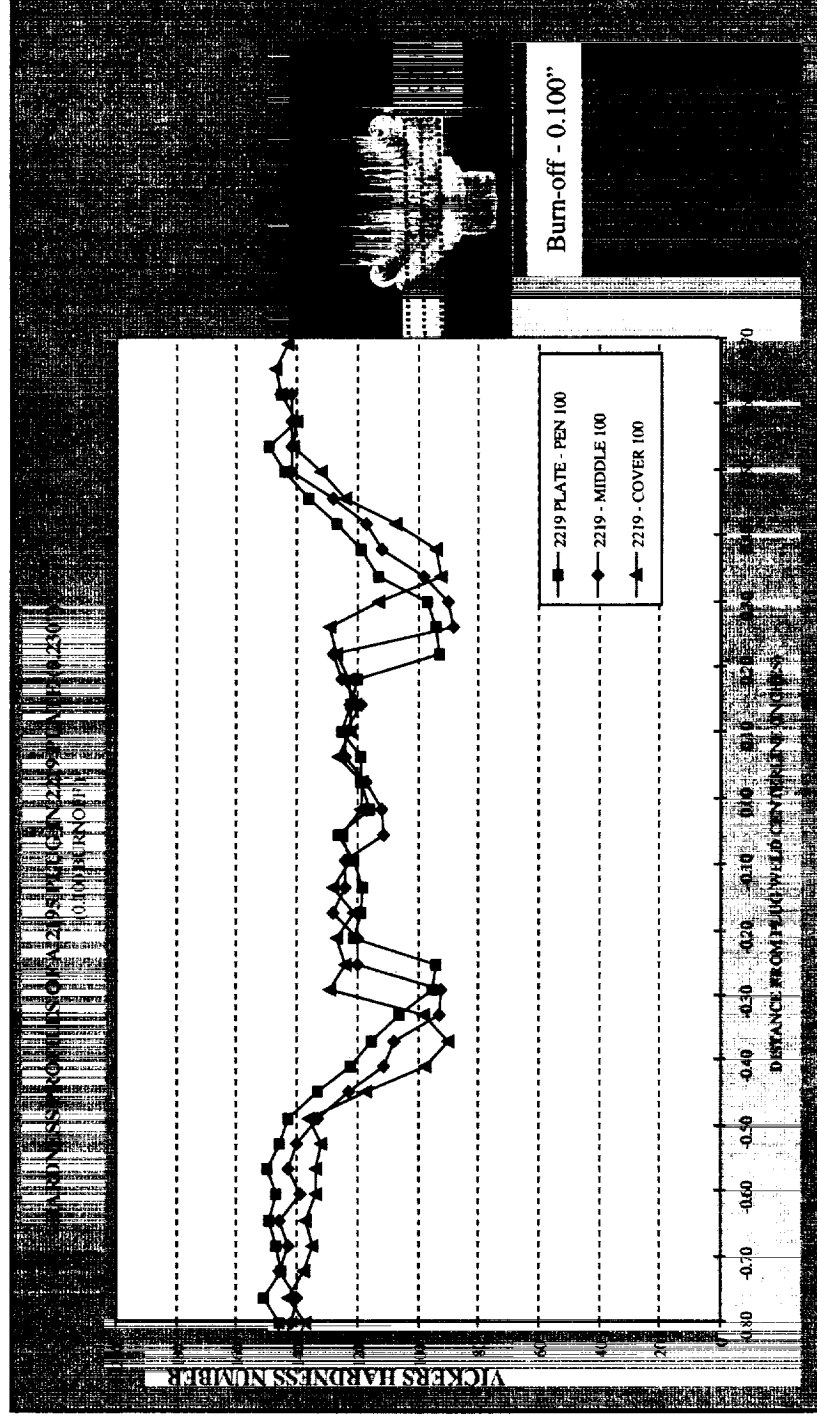
Conclusions

- FPW on Thin (0.140") and Thick (0.500" and 0.650") Gages
 - Demonstrated that FPW can be used on thin and thick gages with modified weld schedule when it is appropriate
 - The strength of FPW was equal or exceeded shaved fusion welds.
- Microstructure Analysis
 - In FPW 2195
 - Plug center: No T_1 and θ'
 - Weld interface: No T_1 and θ'
 - 0.1" HAZ: No T_1 and θ'
 - However, T_1 platelets were found at grain/subgrain boundaries
 - 0.15" HAZ: Partial dissolution of T_1 precipitates.
 - In FPW 2219
 - Weld interface: No θ'
 - 0.1" HAZ: Partial dissolution of θ'
 - 0.2" HAZ: Partial dissolution of θ'
 - HAZ in 2219 plate is narrower than that in 2195 plate. It may be attributed to the higher conductivity of 2219.

Back Up Charts

Mechanical Properties of FPW

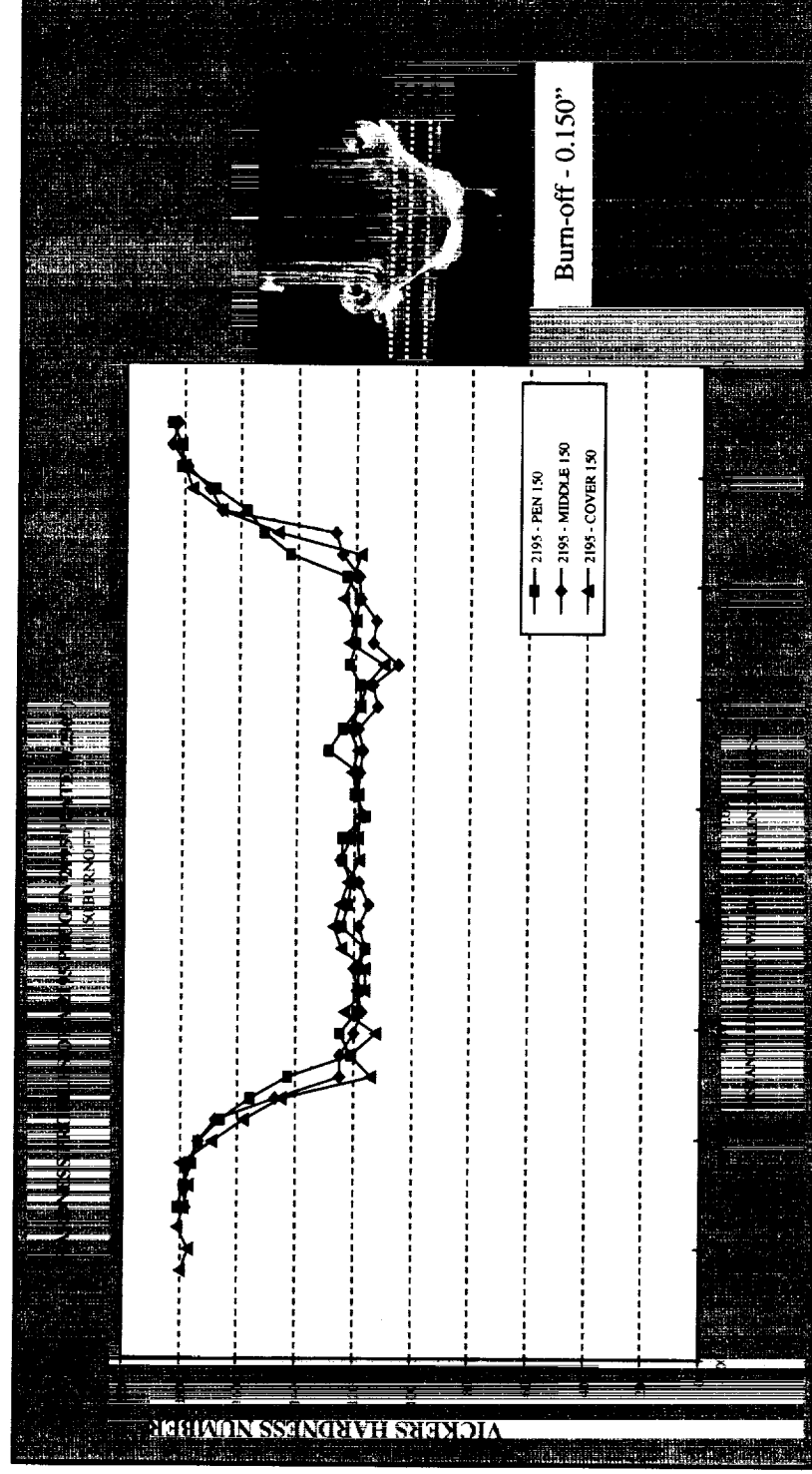
Microhardness Profile



Hardness profile of a 2195 plug in a 0.230 inch 2219 plate

Mechanical Properties of FPW

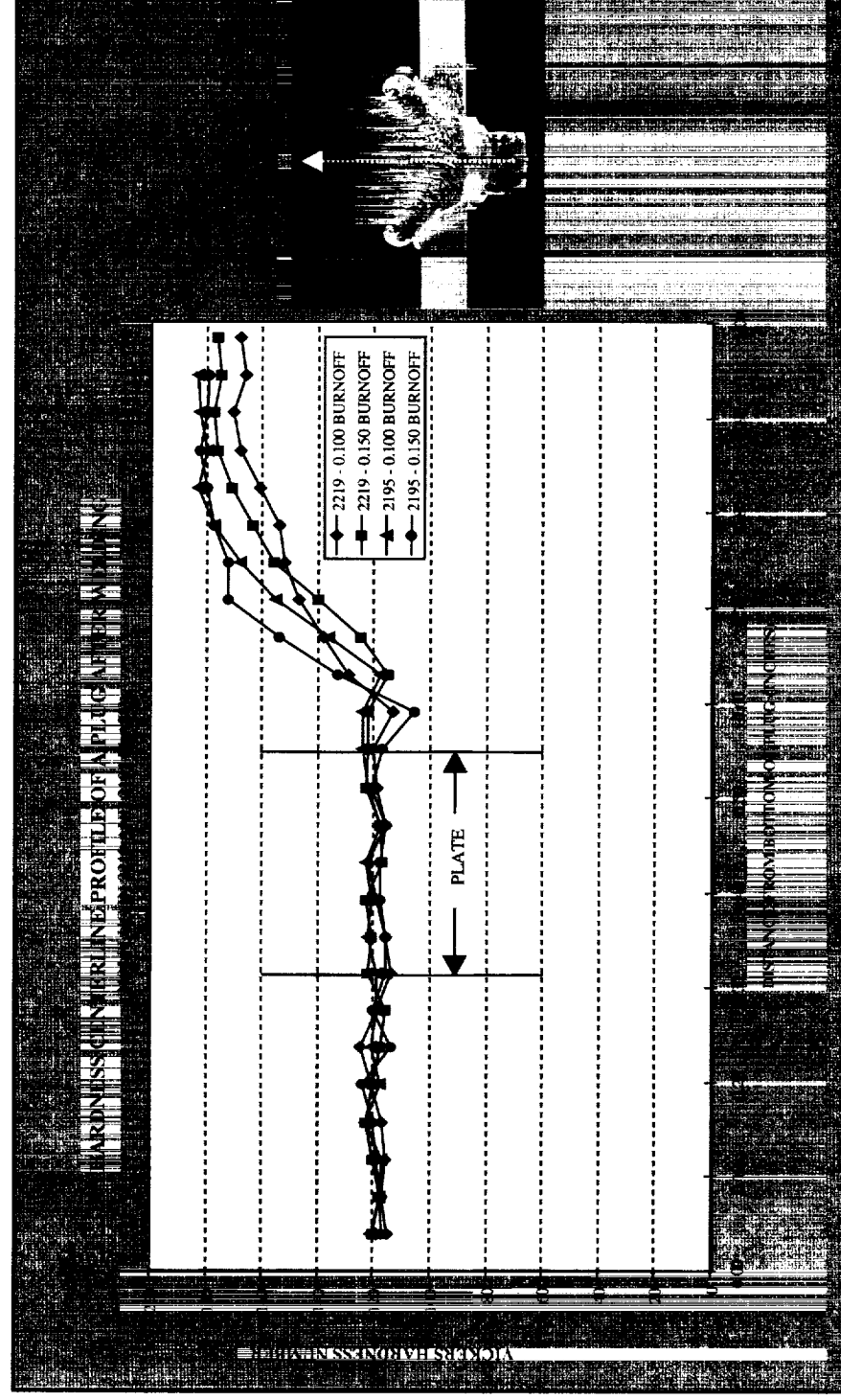
Microhardness Profile



Hardness profile of a 2195 plug in a 0.230 inch 2195 plate

Mechanical Properties of FPW

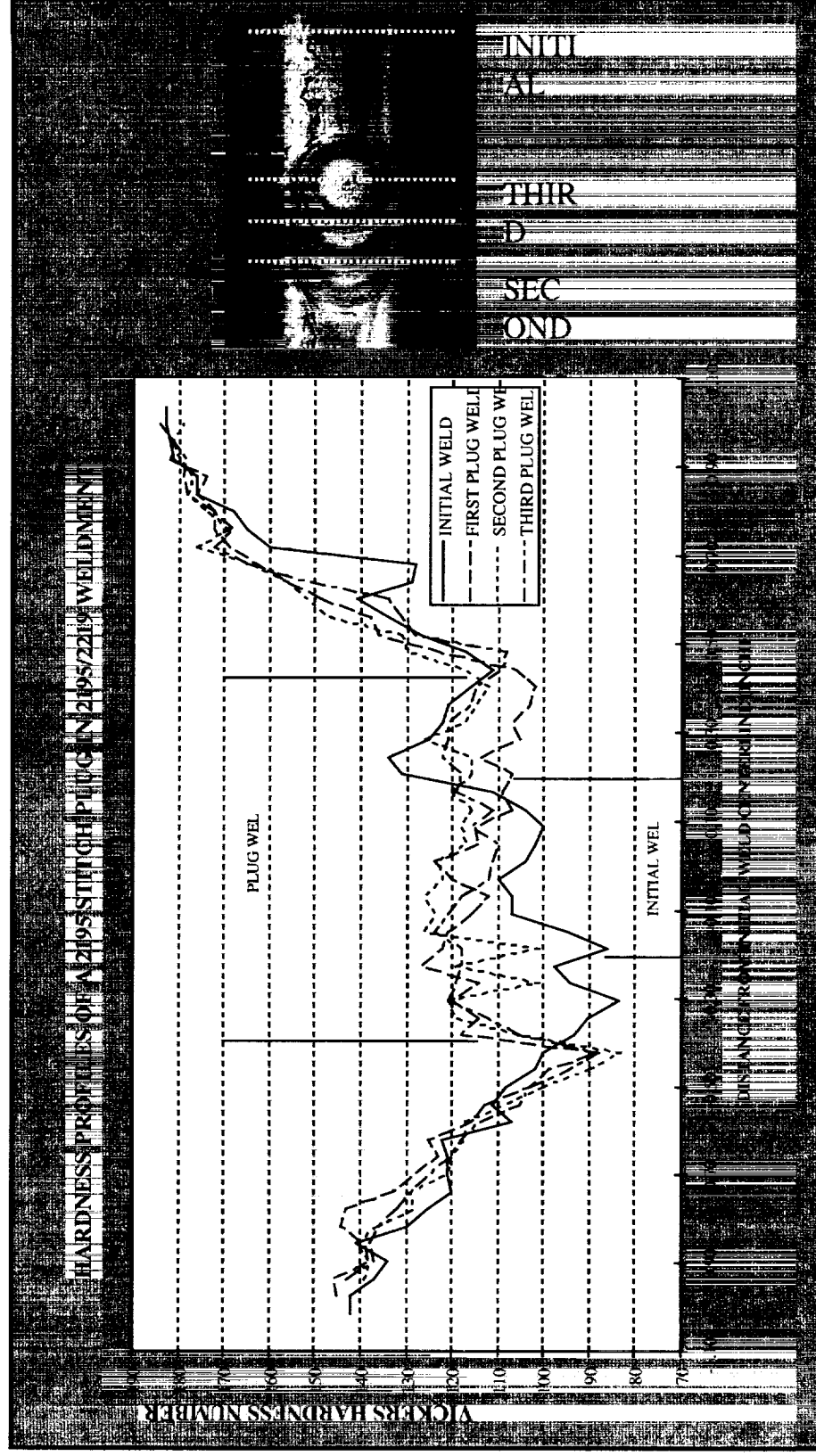
Microhardness Profile



Hardness profile of a 2195 plug in a 0.230 inch 2195 or 2219 plate

Mechanical Properties of FPW

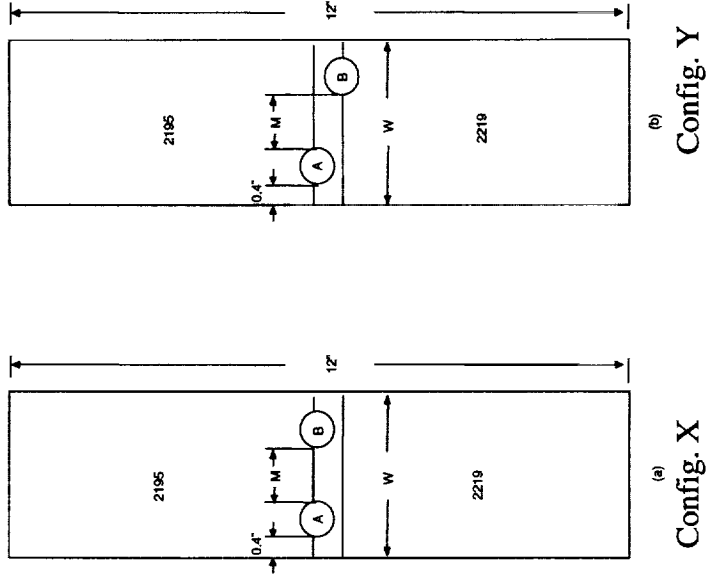
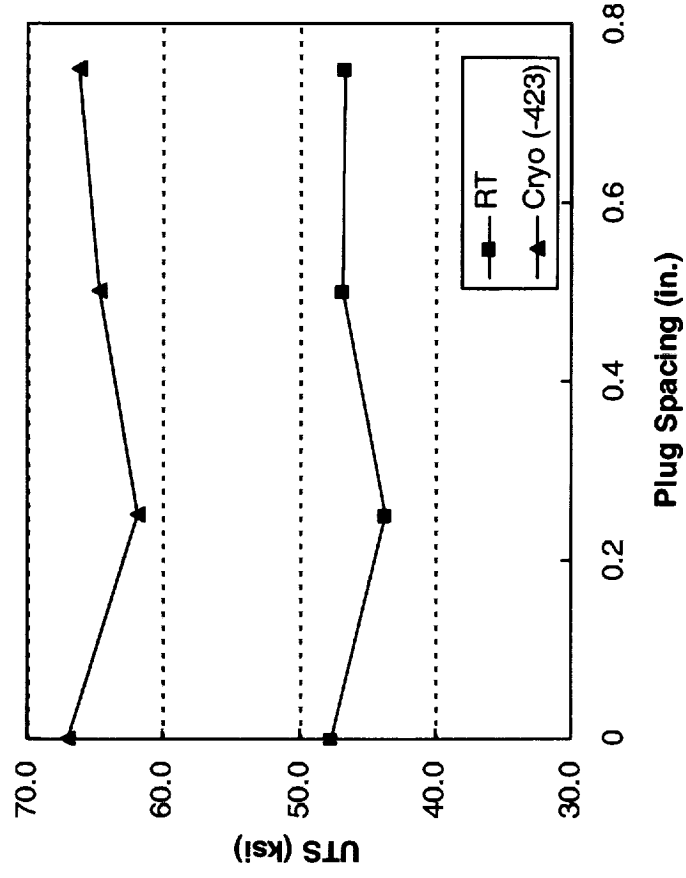
Microhardness Profile



Hardness profile of a triple plug stitch in 2195/2219 weldment

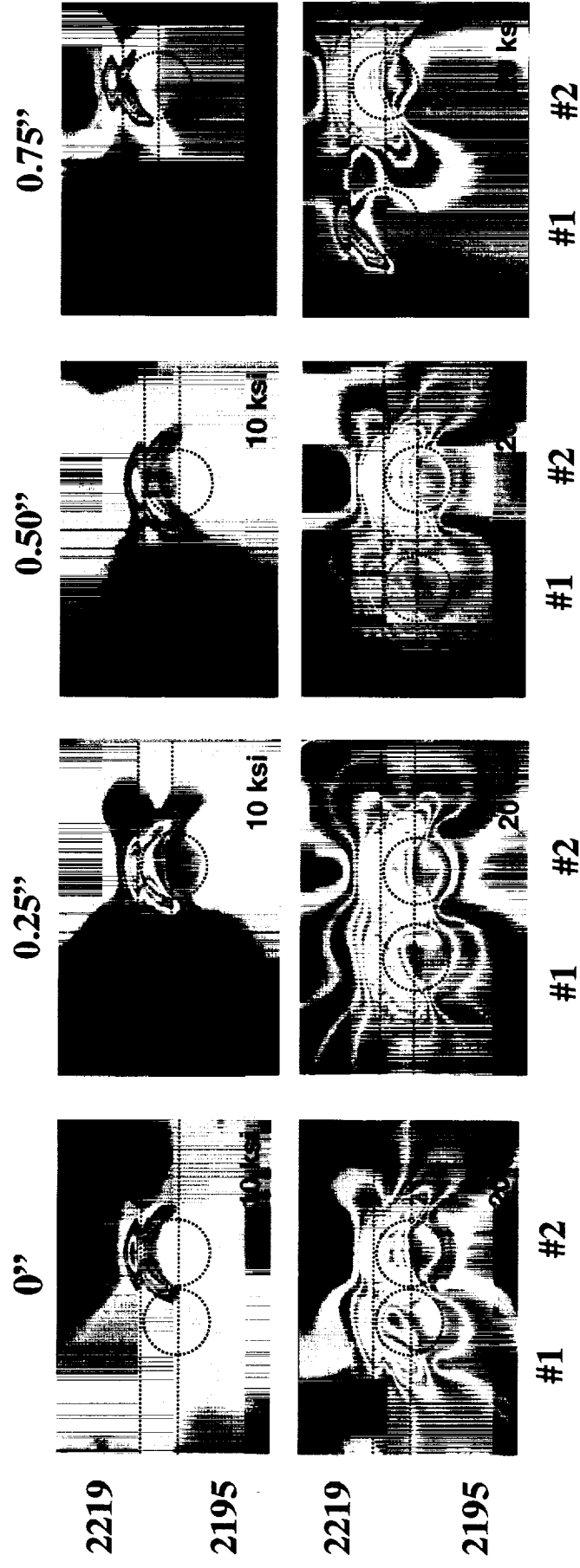
Mechanical Properties of FPW

Plug Spacing (Distance between two plug welds)



Mechanical Properties of FPW

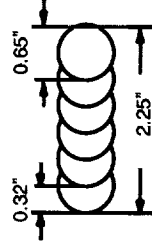
Photo Stress Testing on Plug Spacing



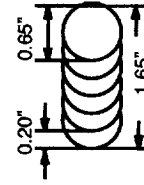
Mechanical Properties of FPW

Long Stitch Weld

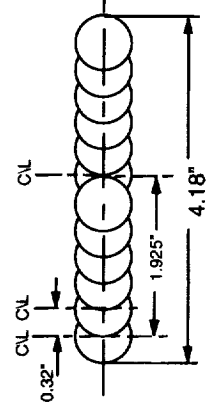
| | | UTS (RT) | UTS (-320F) | UTS (-423F) |
|-------|-------------------------|----------|-------------|-------------|
| 95/95 | 6 Stitch (index=0.32") | 45.7 | 56.5 | 66.4 |
| | | 53.6 | 58.8 | 67.9 |
| | 6 Stitch (index=0.20") | 46.5 | 57.6 | 63.0 |
| | | 49.3 | 55.7 | 64.4 |
| 95/95 | 12 Stitch (index=0.32") | 52.2 | 62.7 | 69.1 |
| | | 49.4 | 67.9 | 72.7 |
| | | | | 68.8 |
| 19/95 | 12 Stitch (index=0.32") | 47.9 | 62.7 | 70.4 |
| | | 45.9 | 64.7 | 66.8 |



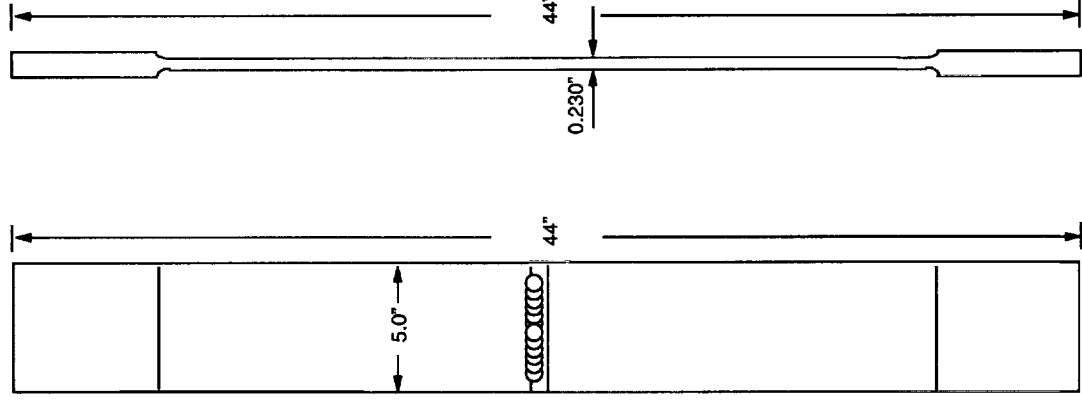
Index=0.32"



Index=0.20"

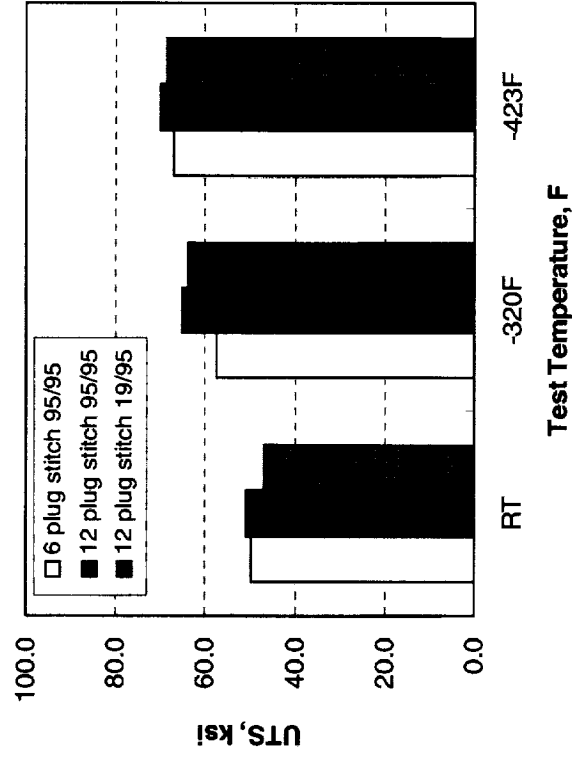


Index=0.32"

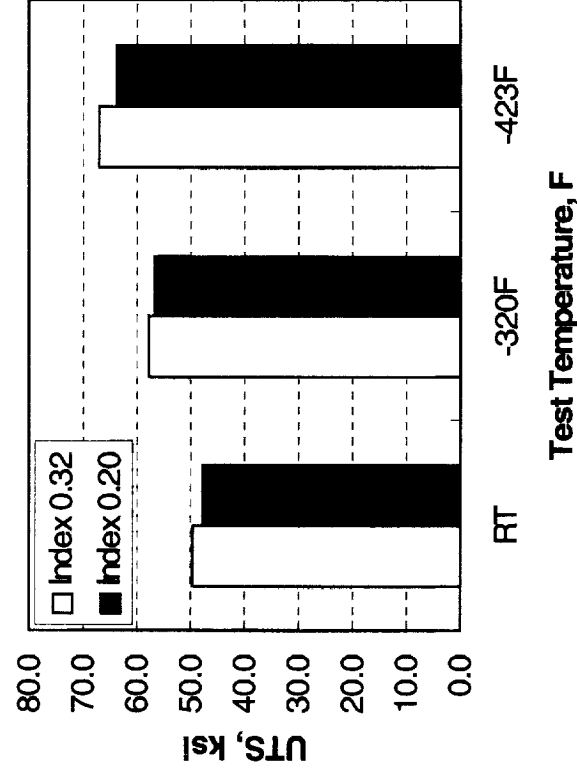


Mechanical Properties of FPW

Long Stitch Weld



Effect of number of plugs in a stitch weld on their strength



Effect of stitch index on strength of stitch welds for 6 plug stitch welds